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Development Of A DC Motor Model And An Actuator Efficiency Model

John C. Watkins
Mike G. McKellar
Kevin G. DeWall

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DEVELOPMENT OF A DC MOTOR MODEL AND AN ACTUATOR EFFICIENCY MODEL[1]

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Idaho National Engineering and Environmental Laboratory

ABSTRACT

For the past several years, researchers at the Idaho National Engineering and Environmental Laboratory, under the sponsorship of the U.S. Nuclear Regulatory Commission, have been investigating the ability of motor-operated valves (MOVs) used in Nuclear Power Plants to close or open when subjected to design basis flow and pressure loads. Part of this research addresses the response of a dc-powered motor-operated gate valve to assess whether it will achieve flow isolation and to evaluate whether it will slow down excessively under design-basis conditions and thus fail to achieve the required stroke time.

As part of this research, we have developed a model of a dc motor operating under load and a model of actuator efficiency under load based on a first principle evaluation of the equipment. These models include the effect that reduced voltage at the Motor Control Center and elevated containment temperatures have on the performance of a dc powered MOV. The model also accounts for motor torque and speed changes that result from the heatup of the motor during the stroke. These models are part of the Motor-Operated Valve In Site Test Assessment (MISTA) software which is capable of independently evaluating the ability of dc-powered motor-operated gate valves to achieve flow isolation and to meet required stroke times under design-basis conditions.

This paper presents an overview of the dc motor model and the actuator efficiency under load model. The paper then compares the analytical results from the models with the results of actual dc motor and actuator testing, including comparisons of the effect reduced voltage, elevated containment temperature, and motor heating during the stroke have on an MOV.

NOMENCLATURE

A	=	Heat transfer area
C_1, C_2	=	Constants
C_p	=	Specific heat
e	=	Efficiency of the stem/stem-nut
emf	=	Back electromagnetic force
h_{cv}	=	Convection heat transfer coefficient
h_r	=	Radiation heat transfer coefficient
I_a	=	Armature current
I_{sh}	=	Shunt current
k, k_1, k_2	=	Constants
M	=	Mass
p	=	Pitch of the worm gear
r	=	Radius of the worm gear
r_m	=	Radius of the motor
R_a	=	Resistance of the armature, series and interpole
R	=	Resistance at temperature T
R_o	=	Resistance at temperature T_o
t	=	time
T	=	Motor temperature
T_{amb}	=	Ambient temperature
T_q	=	Motor torque
T_0	=	Reference temperature
U	=	Heat transfer coefficient
V_a	=	Voltage across the armature
V_b	=	Voltage loss across the brushes
V_m	=	Voltage across the motor
V_{sh}	=	Voltage across the shunt
ε	=	Emissivity
ϕ	=	Magnetic flux
ϕ_a	=	Armature magnetic flux
ϕ_{sh}	=	Shunt magnetic flux
μ	=	Stem/stem-nut coefficient of friction
σ	=	Stefan-Boltzmann constant
ω_m	=	Rotational speed or the motor

[1] Work performed under U. S. Department of Energy Contract No. DE-AC07-99ID13727.

INTRODUCTION

In response to regulatory initiatives, nuclear electric utilities are conducting in situ diagnostic testing of MOVs. The purpose of the tests is to provide assurance that the MOVs are able to operate (close and/or open) against design basis flows and pressures and at design basis operating temperatures and voltages. The utilities generally use one of several commercially available diagnostic test systems to record pertinent diagnostic data during the in situ tests.

The United States Nuclear Regulatory Commission (U.S. NRC) requested that the Idaho National Engineering and Environmental Laboratory (INEEL) develop the capability to independently evaluate in situ diagnostic test data. The need for such capability is driven by the complexity of the situation:

- In situ test data are subject to individual interpretation
- Many of the calculations necessary to evaluate the response of a MOV are not performed by the various diagnostic test systems
- The in situ test data are difficult, if not impossible, to use outside the diagnostic test system environment, because of the proprietary data formats
- Even if the data were available, large volumes of information need to be processed, and many of the calculations necessary to arrive at design-basis performance estimates rely on assessment methodologies that are difficult for either utility personnel or U.S. NRC inspectors to implement.

In response to the U.S. NRC request, MOV researchers at the INEEL developed the motor-operated valve in situ test assessment (MISTA) software; a package that achieves the needed test assessment capability by cross-linking proprietary diagnostic testing software with a commercial data analysis and display software package called DADiSP. The diagnostic vendors have either agreed to cooperate with this effort by providing the information necessary to translate their proprietary data formats to a more universal format that can be recognized by DADiSP, or else their data is already in a format that DADiSP can recognize.

The MISTA software is also capable of independently evaluating the ability of dc-powered motor-operated gate valves to achieve flow isolation and to meet required stroke times under design-basis conditions. MISTA uses INEEL's model of dc motor operation under load and INEEL's model of actuator efficiency under load to perform the assessment. MISTA combines these models with data provided by the user (upstream pressure, differential pressure, motor control center voltage, actuator gear information, stem diameter, stem pitch and lead, etc., along with estimates for MOV variables such as disc friction, stem friction, etc.) as input. The focus of this paper is on how these two models were developed and validated. The actuator model will be discussed first followed by the dc motor model.

DEVELOPMENT OF THE ACTUATOR MODEL

The actuator model is based on a first principle evaluation of a Limitorque SMB type actuator and the physics that influence how it operates. Major components of the actuator are shown in Fig. 1.

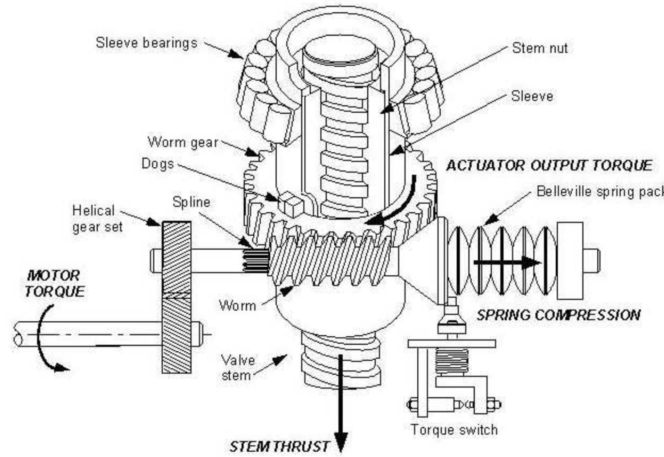


Figure 1. Major components of an MOV actuator.

The input torque consists of the torque delivered by the electric motor to the input side of the gearbox, and the output torque consists of the torque delivered to the stem nut by the worm gear. The gearbox efficiency accounts for losses to friction at the helical gear set, the worm/spline interface, the worm/worm-gear interface, and the associated bearings. Typical efficiency values for SMB actuator gearboxes are in the range of 0.4 to 0.6. The more efficient the gearbox performance (the less the loss to friction), the higher the efficiency value. The gearbox efficiency value does not include motor effects or friction at the stem/stem-nut interface, which are separate calculations.

We begin the development of the actuator model by evaluating the torque losses at various locations within the actuator. We note that the torque at the worm is a combination of the torque out of the motor less torque losses due to the pinion gears and bearing friction losses. The torque at the worm gear will experience some losses at the upper and lower thrust bearing while being transferred to the stem. If we assume that most of the torque loss will occur between the motor and the worm, we can estimate the loss as the torque needed to reverse the worm gear without any output torque bring transferred from the actuator. This torque loss will be referred to as the hotel load and can be estimated using diagnostic test data shown in Fig. 2. The upper figure is the stem torque and the plateau at the zero torque value contains the portion of the test where the motor was reversing the worm gear but no torque was being transferred to the stem. The lower figure is the motor torque and shows that a torque of 1.56 ft-lb was needed to spin the gears without any net output torque being transferred to the stem.

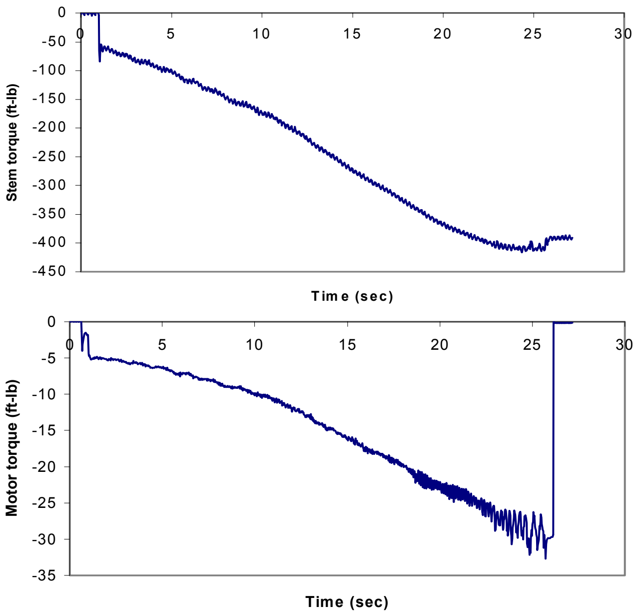


Figure 2. Typical motor and stem torque diagnostic test traces showing the actuator hotel load.

Subtracting the actuator torque loss, or the actuator hotel load, from the motor torque trace and then multiplying the resulting value by the pinion gear ratio will give an estimate of the torque at the worm. Conversely, if we divide the stem torque by the worm to worm gear ratio, we can estimate the torque at the worm gear that was needed to generate the stem torque. The worm/worm-gear efficiency can then be estimated as the worm gear torque from the stem divided by the worm torque from the motor. This efficiency can then be used to estimate the friction between the worm and the worm gear using the following equation.

$$\mu = \frac{1 - e}{\dfrac{2\pi re}{p} + \dfrac{p}{2\pi r}} \tag{1}$$

We can then plot the friction versus the worm gear sliding speed, similar to the method presented in reference [1] and shown in Fig. 3. However, when we compare the results from one test with the results of another test, we find that a very poor relationship emerges, even for the same motor and actuator combination. We then used our experience from the Stellite 6 friction testing and recognized that the load on the surfaces can influence the friction at the interface. As such, we adjusted the worm gear sliding speed to include the influence of load on the gears. The resulting relationship is shown in Fig. 4. This figure contains the results of three tests, a 100% voltage test, an 80% voltage test, and a 60% voltage test using the same motor and actuator. While not shown, the same relationship exists when the actuator was at an elevated temperature. Since the results are repeatable regardless of either degraded voltage or elevated temperature conditions, this relationship can be used to estimate the worm/worm gear friction knowing the loaded sliding speed between the gears.

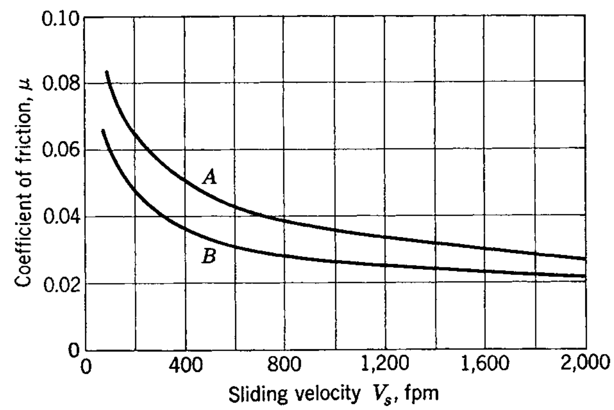


Figure 3. Worm to worm gear friction based on the sliding velocity of the gears.

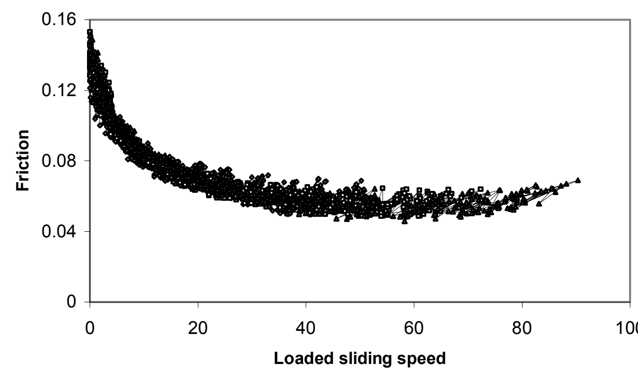


Figure 4. Worm to worm gear friction based on the loaded sliding speed of the gears.

If we apply the above method to different actuators, different motors, and different gear sets within the actuator, we find that the friction to loaded worm gear sliding speed is reproduced. This gives us confidence that the actuator efficiency can be estimated using the above relationship between the worm to worm gear friction and the loaded sliding speed of the worm.

Use of the actuator model in MISTA

To estimate the actuator efficiency using Eq. (1), a user would need to know the worm/worm-gear ratio, the pinion gear ratio, the effective radius of the worm, the centerline distance between the worm and the worm gear, and an estimate of the actuator hotel load. This information should be available from the actuator manufacturer. MISTA would then use the stem thrust at a given stem position and the user's estimate of the stem/stem-nut friction to estimate the stem torque. MISTA would then iterate on the motor speed at a given stem position until the worm to worm gear friction and the actuator efficiency converges. This friction can then be used to estimate the efficiency of the actuator and then, along with the actuator hotel load, used to estimate the torque required from the electric motor.

DEVELOPMENT OF THE DC MOTOR MODEL

The dc motor model is based on a first principle evaluation of a dc motor and the physics that influence how it operates. The model is shown in Fig. 5 and represents a cumulatively compound dc-motor, typical of the dc motors installed on MOVs.

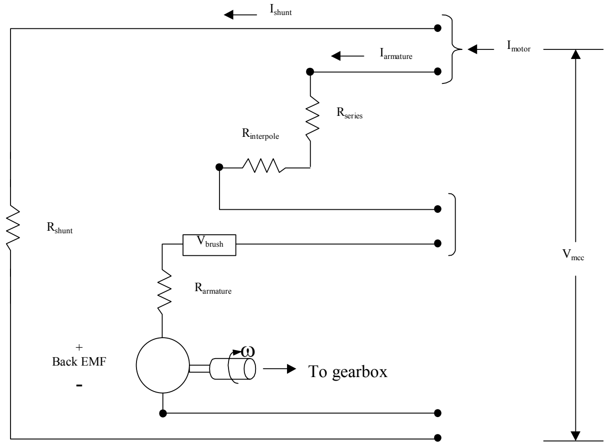


Figure 5. Electrical schematic of a typical MOV dc motor.

Motor physics and development of the motor model

When a wire that is carrying a current is placed in a magnetic field, a force is exerted upon the wire. In a motor, this current carrying wire is part of the rotor, so the force creates a torque that is proportional to the magnetic field, or flux, and to the armature current (the current in the load-carrying wire) or,

$$T_q = k\phi I_a \tag{2}$$

The flux acting on the rotor of a cumulatively compound motor is proportional to the sum of the fluxes of both the series field and the shunt field. The flux is also proportional to the current through the shunt and the series fields, or

$$\phi = \phi_{sh} + \phi_a = k_1 I_{sh} + k_2 I_a \tag{3}$$

Substituting this relationship into Eq. (2) yields a relationship between the torque output of a motor and the current in the shunt and armature, or

$$T_q = kk_1 I_{sh} I_a + kk_2 I_a^2 \tag{4}$$

This expression can be used to estimate the armature current if the motor torque, the shunt current, and the constants are known. These constants are related to the geometry and magnetic properties within the motor and can be estimated by optimizing the motor's performance curves.

The rotation of the armature in the flux field also creates a counter or back electromagnetic force (emf) that opposes the rotation of the armature. The back emf is proportional to the flux and to the rotational speed of the armature, or

$$emf = k\phi\omega_m \tag{5}$$

Substituting the definition of flux from Eq. (2) into Eq. (5), the motor speed can be expressed in terms of the back emf, the armature current, and the motor torque, or

$$\omega_m = \frac{emf\ I_a}{T_q} \tag{6}$$

The voltage drop across the motor is equal to the sum of the back emf, the voltage loss across the brushes, and the armature current times the total resistance, Ra, of the armature, the series field, and the interpole resistance, or

$$V_m = emf + V_b + I_a R_a \tag{7}$$

This expression can be used to estimate the back emf if the motor voltage, brush voltage loss, and the armature current and total resistance are known.

Motor heatup and development of the motor model

During operation, dc motors will heatup while turning against a load. This heatup will become more severe as the motor speed slows and the stroke time increases. We have estimated the temperature response of the dc motor using a lumped thermal capacity model that includes

- Heat input due to the electrical and mechanical losses in the motor
- Heat loss due to convection and radiation out of the motor
- The thermal capacity of the iron and copper in the motor, or

$$\frac{dT}{dt} = \frac{heat\ input - heat\ loss}{thermal\ capacity} \tag{8}$$

The heat input due to electrical and mechanical losses in the motor can be estimated as the difference between the electrical power into the motor and the mechanical power out of the motor, or

$$heat\ input = V_{sh} I_{sh} + V_a I_a - T_q \omega_m \tag{9}$$

The heat loss can be estimated as a heat transfer coefficient times the surface area of the dc motor times the difference in temperature between the motor and the ambient, or

$$heat\ loss = UA(T - T_{amb}) \tag{10}$$

The heat transfer coefficient is modeled as the sum of the convection and radiation heat transfer coefficients. During the optimization process, we determined that the heat conduction from the motor to the actuator was negligible; therefore, it was not included in the model. The convection and radiation heat transfer coefficients are, respectively

$$h_{cv} = C_1 \left(\frac{T - T_{amb}}{2r_m} \right)^{C_2} \tag{11}$$

$$h_r = \varepsilon\sigma\left(T^2 + T_{amb}^2\right)(T + T_{amb}) \tag{12}$$

The thermal capacity of the motor can be estimated as the mass of the iron and copper times the specific heat, or

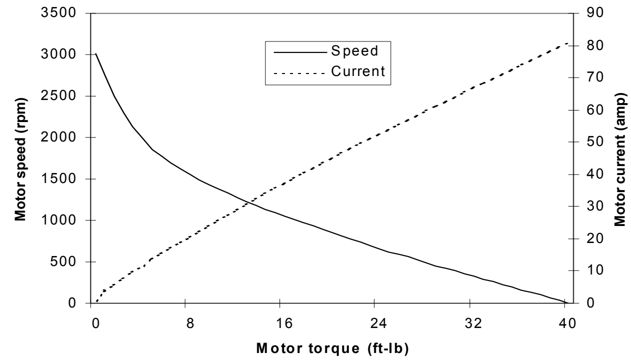
$$thermal\ capacity = MC_p \tag{13}$$

These expressions can be used to estimate the motor heatup if the constants are known. These constants are related to the geometry of the motor and can be estimated by optimizing the motor's performance curves.

From our testing, we observed that as a motor heats up, either due to ambient conditions or due to operation of the motor, its performance decreases. This heatup increases the internal resistances throughout the motor and contributes to the performance decrease. To account for this effect, the change in resistance can be estimated using the following expression; all resistances internal to the motor are adjusted using this relationship.

$$R = R_o \left[\frac{234.5 + T}{234.5 + T_o} \right] \tag{14}$$

The numerous unknown variables in the dc motor model can now be estimated by optimizing the manufacturers motor performance curves. A typical speed versus torque and current versus torque performance curve and a typical temperature rise versus time performance curve are shown in Fig. 6. Both curves are for a 25 ft-lb, 125-volt dc motor.



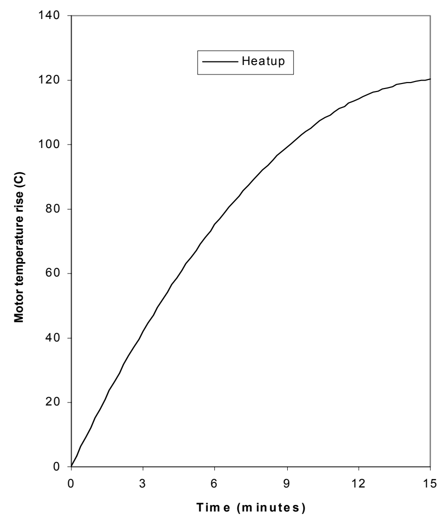


Figure 6. Typical dc motor performance curves.

Model changes to accommodate field wiring

Prior to using the above to estimate the response of a dc powered MOV installed in the field, several modifications were necessary. These modifications include adding the effect of the wire and overload resistances and the effect that wiring differences have on the model. Fig. 7 shows the revised first principle model with the above modifications included.

We also made one additional modification to the above. We were requested to develop a motor model that could be adjusted or fine-tuned to more closely match a motor that may be installed in the field based on the results of diagnostic testing. The generic motor performance curves were used to determine the various unknowns in the equations and as such, the resulting response would reflect the generic information. Based on our understanding of how a dc motor operates and the factors that influence it, we were able to adjust selected parameters to approximate a slightly more powerful or slightly weaker motor relative to the generic information. This capability is obtained by adjusting two parameters that we refer to as the current magnification and the torque magnification. The current magnification adjusts the estimated armature current based upon the torque and the resistance of the armature. The torque magnification adjusts the resistance of the armature.

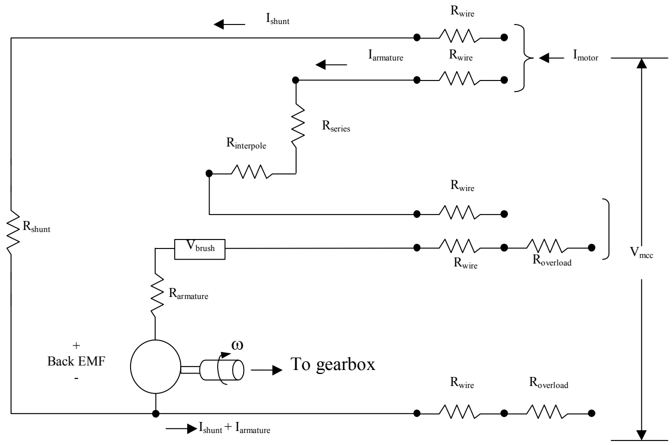


Figure 7. Electrical schematic of a typical MOV dc motor modified to reflect a typical field installation.

USE OF THE ACTUATOR AND DC MOTOR MODELS IN MISTA

The required motor torque, the available voltage at the motor control center, and general MOV characteristics, drives the dc motor model. Fig. 8 presents a flow diagram that outlines the calculations performed at each stem position.

Comparisons of the actuator and dc motor models with the results of testing

To demonstrate the capabilities of the dc motor and actuator model, test data from our reduced voltage and elevated temperature dc motor and actuator testing was used to compare the actual response of the MOV with the estimated response obtained from MISTA. Although only the results from a single motor and actuator are presented, we have used MISTA to simulate all the testing we performed and the results from the other motors and actuators is very similar.

First, Fig. 9 compares the prediction of motor torque, motor speed, motor voltage, motor current, and motor temperature for the 25 ft-lb, 125-volt dc motor at 100% voltage with the results of the testing. The accuracy of the motor torque will depend heavily on the accuracy of the actuator efficiency and the figure shows that the predicted actuator efficiency is very reasonable. The resulting motor torque is also reasonable. The additional motor comparisons presented in the figure indicate that the dc motor model provides a reasonable estimate of the motor response.

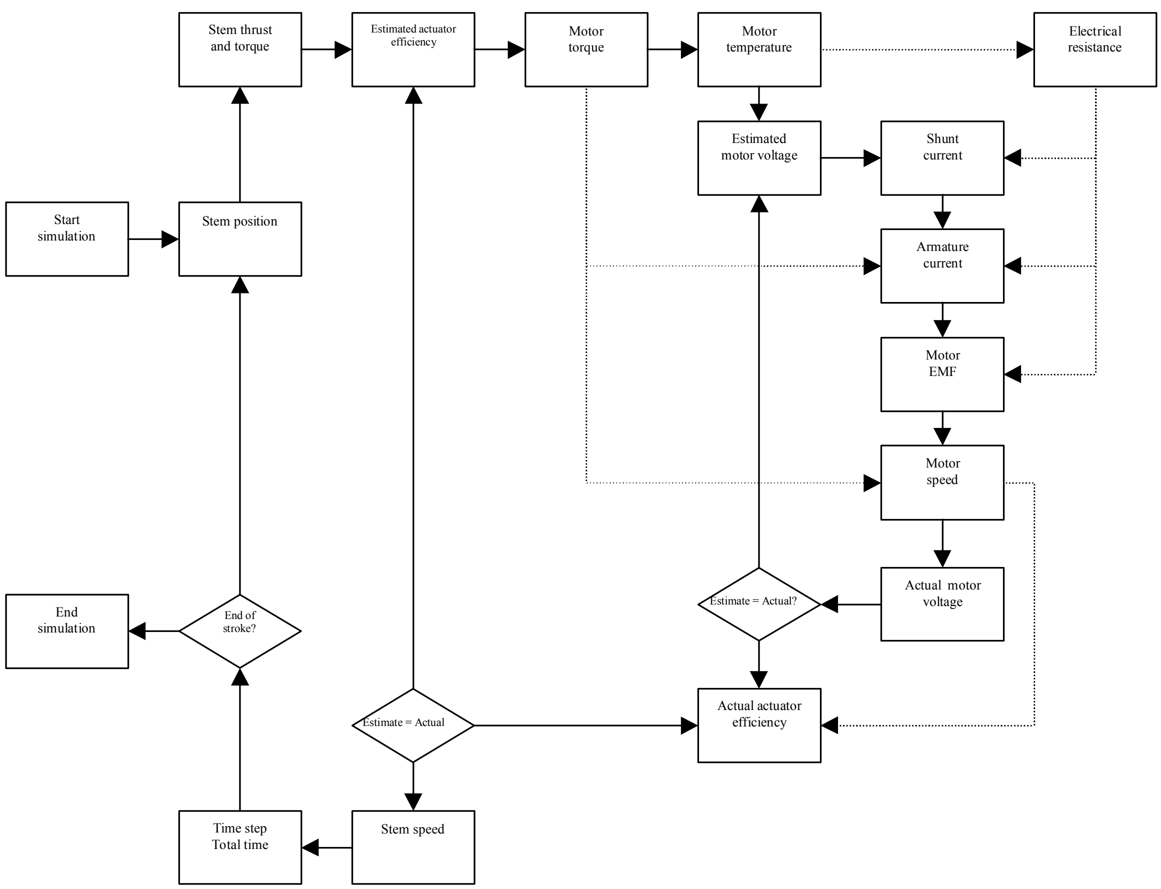


Figure 8. MISTA dc motor and actuator model calculations.

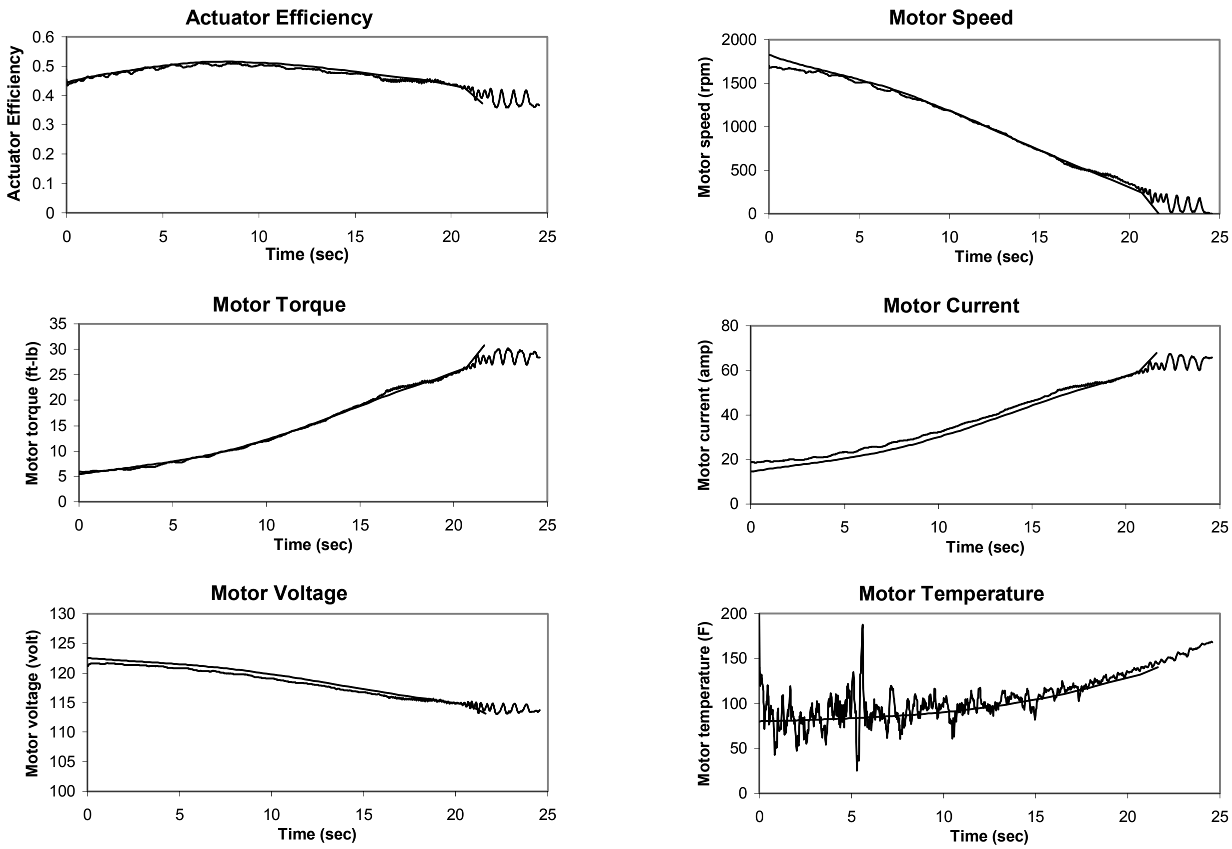


Figure 9. Comparison of actual dc motor and actuator response with the predicted results from the MISTA software.

Additional figures showing selected results from the testing and similar results of the simulation are shown in Fig. 10 through 12. These figures include the effect of reduced voltage only, the effect of elevated temperature only, and finally the effect of both reduced voltage and elevated temperature. On each page, the figures on the left were obtained from the MISTA predictions and the figures on the right were obtained from testing. In general, the results of the dc motor and actuator model provide a reasonable estimate of the response of the actual dc motor and actuator.

CONCLUSIONS

This paper presents the results of an INEEL research project to enhance the capabilities of the MOV in situ test assessment (MISTA) software. Two new first principle models have been developed and added to the software. The first model is based on a first principle model of an actuator that allows the efficiency of an actuator to be accurately estimated. The second model is based on a first principle model of a dc-powered electric motor that allows the response of the electric motor to be accurately estimated as the motor actuator closures a valve against pressure and flow loads. Both models allow the user to accurately estimate the response of a valve, actuator, and dc motor during the closure cycle of a motor operated valve.

We are preparing to validate the MISTA software and the actuator and dc motor models during 2001 and should be completed with this effort by the end of 2001.

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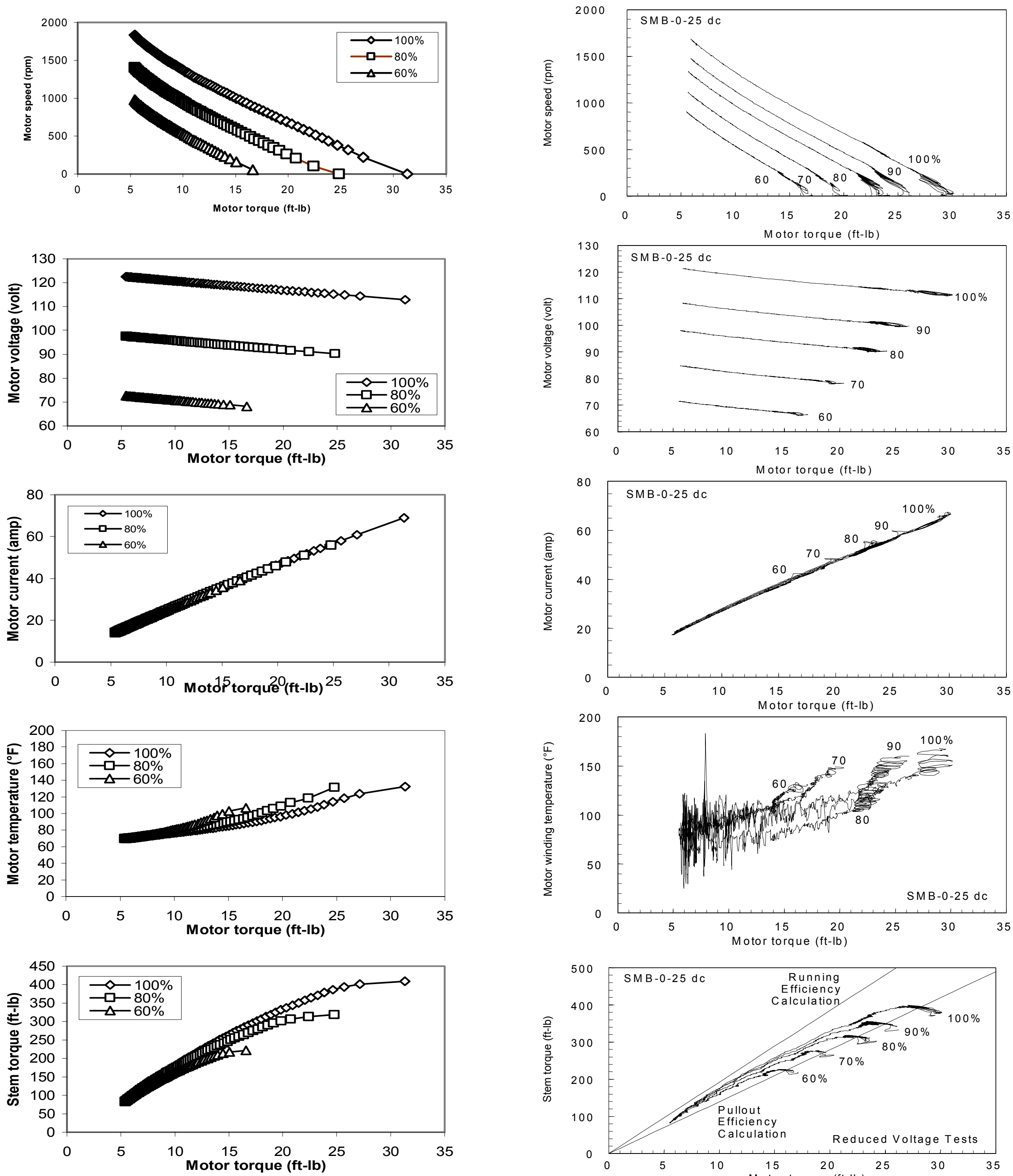

Figure 10. Comparison of the effect of reduced voltage on the actual dc motor and actuator response with the predicted results from the MISTA software.

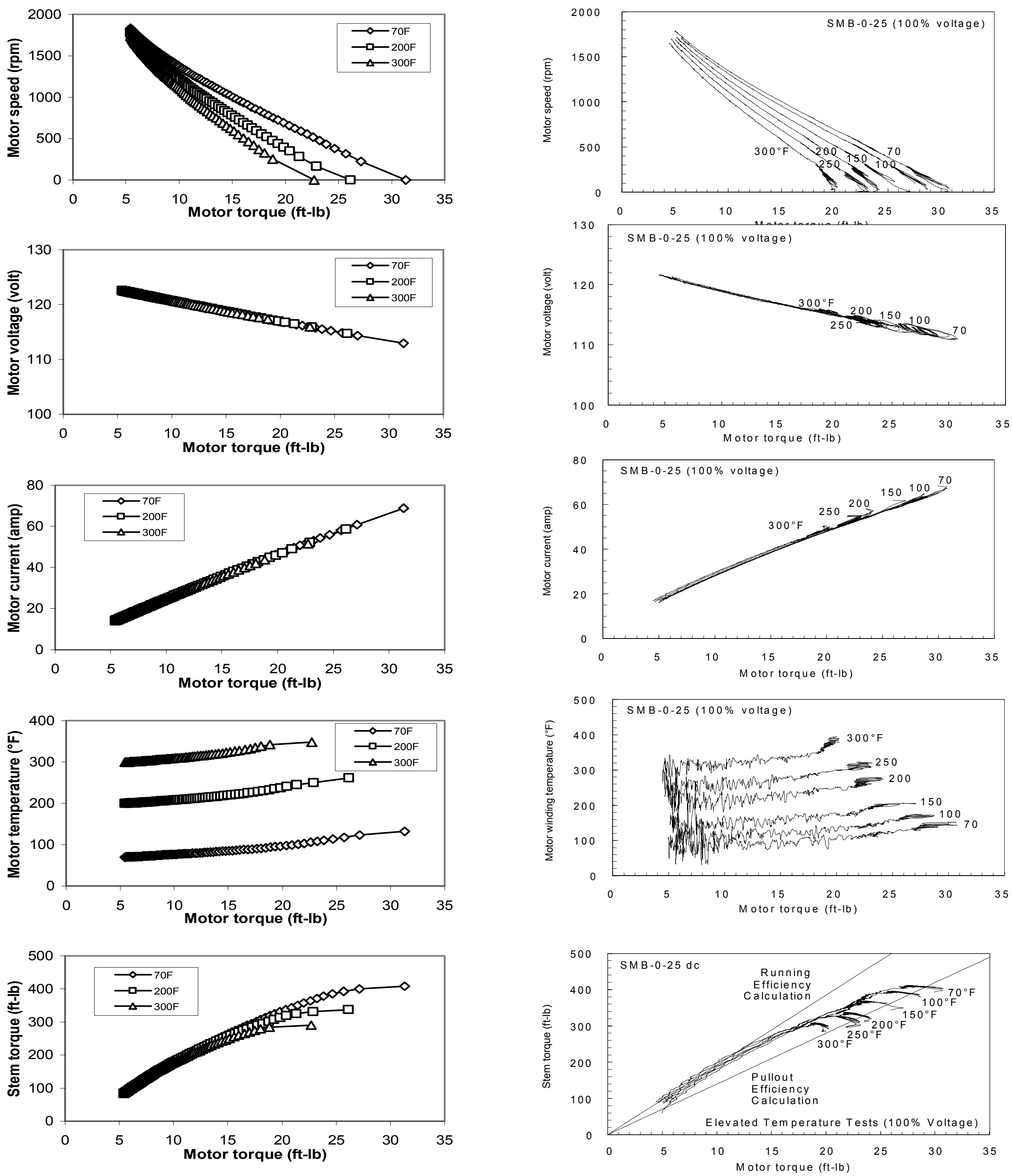

Figure 11. Comparison of the effect of elevated temperature on the actual dc motor and actuator response with the predicted results from the MISTA software.

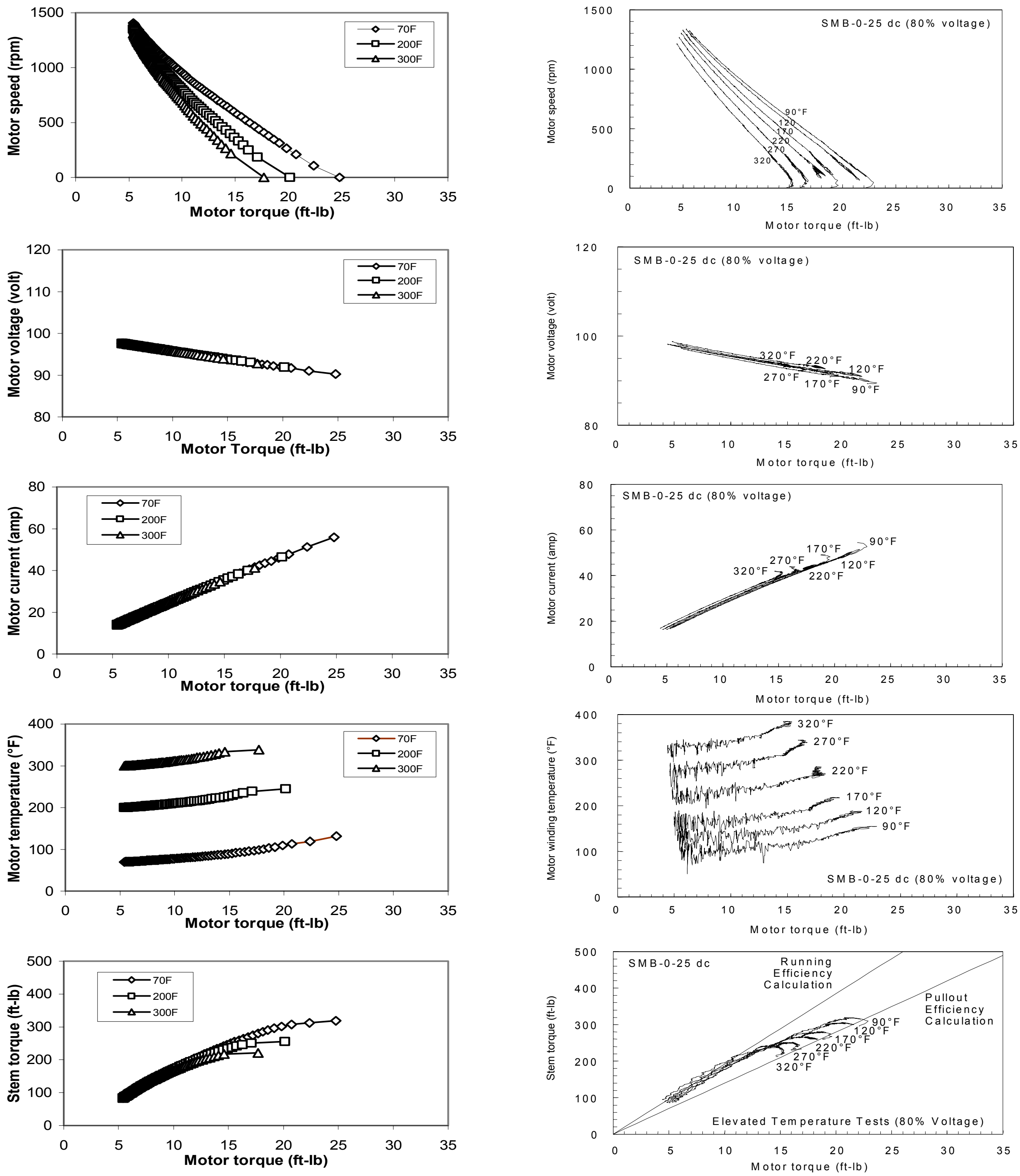

Figure 12. Comparison of the effect of reduced voltage and elevated temperature on the actual dc motor and actuator response with the predicted results from the MISTA software.